91802
new 82-10

ontario hydro
research division

COMPLIMENTARY COPY
Please Credit Ontario Hydro Research if
Reproduced in Whole or in Part.

EXECUTIVE SUMMARY

TRITIATED WASTE CONDITIONING PART III
(a) PERFORMANCE OF CONTAINERIZED AND ENCAPSULATED WASTE FORMS

J.P. Krasznai
Chemist
Chemical Research Department

The Darlington Tritium Removal Facility will generate both liquid and solid tritiated waste. Liquid waste will have to be conditioned and packaged prior to disposal to minimize the releases of tritium to the environment. The conditioning requirements for solid tritiated waste are presently under investigation.

Earlier work on the conditioning of aqueous tritiated waste has shown that solidification by itself in either cement or an organic polymer matrix is inadequate to meet a tritium (as HTO) release target of 1×10^{-3}% per day.

Encapsulating the solidified waste in a 1-cm thick layer of water extendible polyester resin reduced the release rate to 1.3×10^{-4}% per day over a 150-day leaching period. The release rate however, increased to 1.7×10^{-3}% per day when averaged over the subsequent 600-day leaching period.

Encapsulation, however, is a difficult process and the information presented in this report compares encapsulation with simple containerization in a low water permeable material such as polyethylene. The results indicate that the same degree of tritium (as HTO) retention can be achieved by replacing a 1-cm thick encapsulating layer of polymer resin with a .14-cm thick high density polyethylene container. Consequently, encapsulation should not be pursued further for this type of waste.

Leaching data has shown that even for the short exposure times encountered (typically 4-5 hours) the components of the polymer resin solidification agent permanently increase the water permeability and hence tritium releases from the polyethylene containers.

job	file	date	report no.
740632-210-462	837.83	November 29, 1985	85-279-K

Three solutions are possible to circumvent this problem:

1. compensate for the effect of the interaction by increasing the thickness of the container;

2. use a different solidification agent such as cement which is not expected to have an effect on the permeability of water through polyethylene;

3. use polyethylene containers which have been treated to make them resistant to the resin components.

It is recommended that the nature of the interaction between resin and polyethylene be investigated in order to select the most cost effective solution.

The permeability constant of tritiated water through polyethylene has been determined. The range of values 1.9 - 9.3 x 10^{-7} $\frac{\text{Ci cm}}{\text{cm}^2 \cdot \text{Ci/cm}^3 \cdot \text{d}}$ agree well with published data. For those specimens where the interaction between the container and the polymer resin components is the greatest, the permeability constant is 2.75 x 10^{-6} $\frac{\text{Ci} \cdot \text{cm}}{\text{cm}^2 \cdot \text{Ci/cm}^3 \cdot \text{d}}$. For the sake of conservatism, this value has been used to determine the required container thickness to meet the prescribed tritium release target of 1 x 10^{-3}% per day. It is expected, however, that by adopting one of the three solutions stated above, thinner containers could be used or alternatively the release rates would be reduced below the target value.

91802
new 82-10

ontario hydro
research division

To: Mr. H.N. Isaac
Manager
Nuclear Materials Management
Design & Development - Gen

TRITIATED WASTE CONDITIONING PART III
(a) PERFORMANCE OF CONTAINERIZED AND ENCAPSULATED WASTE FORMS

J.P. Krasznai

Earlier work on the conditioning of aqueous tritiated waste has shown that solidification by itself is inadequate to retain tritium in the waste. Encapsulation of the solidified waste in a 1-cm thick water extendible polyester resin matrix was shown to reduce the rate of loss of tritium to 1.7×10^{-3}% per day averaged over a 750-day leaching period. It has been shown in this work that the same degree of tritium retention can be achieved by replacing the encapsulating layer by a 1.4-mm thick high density polyethylene container. The components of the water extendible polyester resin increase the permeability of water through polyethylene which results in an increase in the tritium loss rate. The nature of the interaction between polyethylene and water extendible polyester resin should be investigated because there are barriers available which are designed to prevent attack of polyethylene by some solvents. The rate of loss of tritiated water from the waste packages expressed as a fraction of the original tritium activity is approximately proportional to the ratio of the specimen surface area and volume and inversely proportional to the container thickness. A permeability constant of between $1.9\text{-}9.3 \times 10^{-7}$ $\frac{Ci \cdot cm}{cm^2 \cdot Ci/cm^3 \cdot d}$ has been measured for tritiated water through high density polyethylene.

INTRODUCTION

Work is continuing to develop conditioning systems for high and intermediate level tritiated waste arising from the Darlington Tritium Removal Facility. The waste streams from this facility have recently been quantified/1/ in Table I.

job	file	date	report no.
740632-210-462	837.83	November 29, 1985	85-279-K

TABLE I

Type of Waste	Activity Level	Estimated Max Vol of Waste
Liquid		
(a) Water	10^{-6} Ci/kg	200 m^3/a
(b) Electrolyte (25% KOH)	0.5-1.0 Ci/kg	0.025 m^3/a
(c) Pump Oil	0-50 Ci/kg	0.075 m^3/a
Solid		
(a) Low Activity	<0.2 Ci/m^3	132 m^3/a
(b) Medium Activity	0.2-100 Ci/m^3	0.4 m^3/a
(c) High Activity	>100 Ci/m^3	1.3 m^3/a

Part I and II of this program have focused on the immobilization of aqueous tritiated waste/2/ and the leaching performance of the resulting solidified waste forms/3/. Two performance criteria were established at the beginning of the work in order to evaluate the results:

(1) Tritium releases from the waste forms must not exceed $1x10^{-3}$% per day.

(2) The waste form package must retain its integrity for 150 years (12 tritium half lives) in a disposal environment.

Based on the first criterion it was shown that tritium as tritiated water cannot be adequately immobilized by solidification alone in either cement or a water extendible polyester resin matrix. Tritium releases under these conditions were 0.1% per day for WEP resin solidified waste and 0.4% per day for cement solidified specimens. However, when the solidified specimens were encapsulated in various materials, the daily tritium loss rate was reduced by three orders of magnitude when the encapsulating material was WEP resin ($1.3x10^{-4}$%/day over a 150-day leaching period). However, over the subsequent 600-day leaching period, the tritium loss rate increased to $1.7x10^{-3}$% per day. In these experiments the containers in which the waste forms were made were removed prior to leaching. Consequently the contribution of the container as a barrier against tritium loss was not measured. This is an important consideration in view of the fact that encapsulation is a more difficult and costly process to implement than simple containerization. The work reported here addresses the contribution of the container as a barrier against tritium (as tritiated water) loss.

As Table I indicates, tritiated aqueous waste with the exception of the electrolyzer fluid will not need conditioning by virtue of its low tritium content. The rationale for the work in this report is not therefore to develop waste conditioning techniques for aqueous waste but rather to determine the degree of transport of tritiated water through different barriers. Tritiated water is one of three forms of tritium present in waste from the Tritium Removal Facility (TRF). The other two forms are tritium gas as HT, DT and T_2 and tritiated hydrocarbons formed when tritium is exposed to organic liquids such as pump oil.

The objectives of Part III of the tritiated waste conditioning program are therefore four fold:

(a) to determine the extent of tritiated water release from containerized and encapsulated waste forms of various sizes and thicknesses,

(b) to develop solidification treatments for tritiated pump oil and electrolyzer fluid,

(c) to determine the leaching performance of the waste forms formed in (b),

(d) to determine the required degree of waste conditioning for tritiated solid wastes from the TRF.

As mentioned earlier, this report will focus on objective (a) exclusively. Work is in progress on the other objectives and will be reported in subsequent reports.

EXPERIMENTAL

Choice of Containers

In view of the requirement that the waste container retain its integrity for 150 years and the fact that it is difficult to guarantee the container material whether metallic or non metallic for this length of time, we have assumed a multibarrier concept for packaging tritiated waste. It consists of the immobilized waste (Figure 1) in a primary container. In practice this would be the same container in which the tritiated liquid or solid was immobilized. The primary container would be designed to meet the first performance criterion. If this is not feasible then an encapsulating layer would be added such that it and the primary container provided the required barrier against tritium loss. The secondary container which would not be credited as a tritium barrier would serve as a mold for the encapsulating layer and as an overpack for the primary container. In this work we have investigated polyethylene as the

primary container and compared it with water extendible polyester resin. Polyethylene was selected because (after polyvinylidine chloride (SARAN)), it has the lowest water permeability of the common polymers/4/ and it is readily available.

Two types of high density polyethylene containers were used. Off-the-shelf 25-mL, 125-mL and 500-mL "Nalgene" containers were used to investigate the effect of specimen surface area/volume ratio on the release of tritium. In order to study the effect of wall thickness on the rate of tritium release, containers (Figure 2) were fabricated of constant internal volume but with 1-cm, 0.5-cm and 0.2-cm walls. The sealing arrangement was by means of a neoprene 'O' ring compressed via the lid by two aluminum flanges. As an added precaution against water ingress, RTV silicone sealant was applied to the crevice between the lid and the container body.

Solidification of Tritiated Aqueous Waste

As was mentioned in the introduction, solidification using WEP resin was marginally better than cement from the point of view of tritium release from the solidified specimens. In view of this and the fact that it cures within 24 hours to its maximum strength, it was used in the experiments reported here as the solidification medium. The preparation of tritiated WEP resin specimens has been described in detail in Appendix 2 of reference 3. Bruce NGS moderator water containing 19.3 Ci tritium/kg was used and diluted to appropriate concentrations using distilled water. Table 2 summarizes the physical characteristics of all the samples used in this study.

Encapsulation of Solidified Specimens

The methodology used to encapsulate waste specimens in water extendible polyester resin is described elsewhere/3/. The preparation of replicates which behave identically has been a problem because it is difficult to obtain a leak tight joint between the wire basket holding the waste form and the encapsulating material. To avoid this problem a single piece of copper wire was fixed with epoxy glue to the polyethylene container cap which was used to suspend the waste form in the encapsulating material mold. The WEP resin encapsulating material was then poured over the waste form and allowed to set for 4 - 5 hours. The suspending wire was then cut flush with the top of the solidified specimen and a 0.5-cm cap of WEP resin was poured on top of this to minimize the possibility of leakage at the wire/WEP interface (Figure 3). It is recognized that this is a somewhat cumbersome process for encapsulation and would not be practical for field application. However it is used here for the sake of evaluating the concept of encapsulation not to develop the process for it.

TABLE 2

Sample	Sample Description	Dimension of Waste Specimen d(cm)*h(cm)	Container Thickness cm	Avg Surface Area of Composite (cm^2)	Avg Volume of Composite (cm^3)	SA/V_c (cm^{-1})	Initial Tritium Activity (mCi)
W1 W2	Liquid Water in 500 mL HDPE Container	8.8*7.4	0.13	337.4	483.6	0.71	130.56
C1 C2	Solidified WEP in 500 mL HDPE Container	8.8*8.0	0.13	354.3	519.4	0.68	120.57 125.32
C1A C2A	Unsolidified WEP Emulsion in 500 mL HDPE Container	8.8*8.0	0.13	354.3	519.4	0.68	151.68 158.00
C3 C4	Solidified WEP in 125 mL HDPE Container	4.8*5.2	0.09	117.9	99.9	1.18	101.89 103.72
C5 C6	Solidified WEP in 25 mL HDPE Container	3.3*2.8	0.10	48.2	25.1	1.92	129.42 130.58
PE1 PE2	Solidified WEP in Fabricated HDPE Container	8.0*8.0	1.00	443.0	722.6	0.61	117.50 122.11
PE3 PE4	Solidified WEP in Fabricated HDPE Container	8.0*8.0	0.50	395.1	601.2	0.66	117.80 115.08
PE5 PE6	Solidified WEP in Fabricated HDPE Container	8.0*8.0	0.20	368.6	539.4	0.68	116.03 117.87
E1 E2	Solidified WEP in 500 mL HDPE Container Encapsulated in WEP Matrix	8.8*8.0	0.13 (container) 0.85 (encapsulant)	370.9	822.5	0.45	119.19 118.94

HDPE: HIGH DENSITY POLYETHYLENE

Leaching of Specimens

All specimens except C3, C4, C5 and C6 were leached in 3500 mL of distilled water. 830 mL and 900 mL of distilled water were used as leachant for specimens C3, C4 and C5, C6, respectively. The specimens were completely submerged on their side in the leachant. Since the density of the WEP resin specimens was less than the density of the leachant some of the specimens were weighted down using lead shot. To minimize the quantity of waste liquid, the leachant was not changed but rather 1-mL samples were extracted from the leachant containers at prescribed intervals, mixed with 15-mL liquid scintillation cocktail, PCS-II, and counted on a liquid scintillation counter.

RESULTS AND DISCUSSION

The cumulative fractional release of tritium as tritiated water from the composite specimens is expected to be dependent on specimen size (surface area/volume ratio), container thickness, the type of container material and the method of solidification of tritiated water. The container material was high density polyethylene in all the specimens. The cumulative fractional release data can be expressed three ways.

$$CFR = \frac{\Sigma a_n}{a_o} \tag{1}$$

where Σa_n = total amount of tritium leached from the composite in the leach period and a_o is the original quantity of tritium in the waste specimens at the beginning of the leaching period. Expressed this way, the release data from polyethylene contained specimens is expected to be dependent on both specimen size and container thickness. If the release data is multiplied by the container thickness then this normalized cumulative fractional release will be dependent on specimen size only.

$$CFR(cm) = \frac{\Sigma a_n}{a_o} \cdot \ell \tag{2}$$

where ℓ is the average thickness of the polyethylene container. Similarly cumulative fractional release can be normalized to make it independent of specimen size by dividing it by the ratio of the surface area SA and volume V_c of the specimen.

$$CFR(cm) = \frac{\Sigma a_n}{a_o} \cdot \frac{V_c}{SA} \tag{3}$$

Effect of Specimen Size

Figures 4, 5, 6 and 7 show the leaching behaviour of three different sized specimens containing approximately equal amounts of tritium as tritiated water. The leaching period was 200 days. As Figure 7 indicates, the tritium loss rate increases in the order C5,6 > C3,4 > C1,2 > W1,W2. However, not only the surface area/volume ratio of the specimen, but also the container thickness increases in this order. The cumulative fractional release rates have therefore, been normalized in Table 3 to take this point into consideration. With the exception of the data for specimen C1, the cumulative fractional release rate increases approximately linearly with an increase in the ratio of the surface area and volume of the specimens (Figure 12). The slope of this line, 2.97×10^{-7} $\frac{Ci.cm}{cm^2.Ci/cm^3.day}$ is the permeability constant & is in excellent agreement with the values calculated in Table 6.

TABLE 3

Sample	Container Thickness (cm)	(a) SA/V (cm^{-1})	CFR Rate $day^{-1} \times 10^6$	(b) CFR Rate $cm.day^{-1} \times 10^6$
W1 W2	0.13	0.75	1.1 1.0 } 1.1±0.1	0.14 0.13 }0.14±0.01
C1 C2	0.13	1.45	7.5 5.2 } 6.3±1.1	0.98 0.68 }0.82±0.16
C3 C4	0.09	2.62	7.1 6.6 }6.8±0.2	0.64 0.59 }0.62±0.02
C5 C6	0.10	4.30	12.3 12.9 }12.6±0.3	1.23 1.29 }1.26±0.03

(a) V is the volume of tritiated water in the specimen.
(b) normalized to constant container thickness

Effect of Solidification

An interesting observation is that the tritium release rate (Table 4) is a factor of six higher when the tritiated water is solidified in water extendible polyester resin than when it is left in the liquid state in the container. Figure 9 illustrates this point. A number of possible explanations were proposed:

(a) The presence of a small leakage path into the solidified specimens.

(b) The high exotherm associated with the curing of the WEP resin increasing the solubility and hence permeability of water through the polyethylene container.

(c) The components of the WEP resin namely styrene and vinyl ester and possibly the catalyst methyl ethyl ketone peroxide change the structure of the polyethylene and hence its permeability to water.

TABLE 4

CUMULATIVE FRACTIONAL RELEASE RATES FROM SPECIMENS

Sample	Cumulative Fractional Release Rate (cm/day) $\times 10^6$	% Cumulative Release Rate (day^{-1}) $\times 10^4$
W1 W2	1.5 1.4 } 1.5 ± 0.1	1.1 ± 0.1
C1 C2	11.0 7.7 } 9.3 ± 1.6	6.3 ± 1.1
C1A C2A	42.8 40.7 } 41.8 ± 1.0	28.4 ± 0.7
PE1 PE2	0.8 0.7 } 0.8 ± 0.1	0.5 ± 0.1
PE3 PE4	6.4 3.0 } 4.7 ± 1.7	3.1 ± 1.1
PE5 PE6	7.2 9.0 } 8.1 ± 0.9	5.5 ± 0.6
E1 E2	2.0 0.7 } 1.4 ± 0.7	0.6 ± 0.3

The possibility of pinhole leaks into the solidified specimens can be readily discounted in view of the fact that

(a) the tritium release rates from these specimens were very much lower than from samples which were known to have small leaks,

(b) the liquid sample specimens W1 and W2 consistently exhibited lower release rates than all of the solidified specimens in similar thickness containers, and

(c) if leaks were present then the degree of leakage would have to be the same between replicates since in most cases replicates agreed very well with each other. This is highly improbable.

A peak temperature of 97°C was measured when a 500-mL (50:50 water:WEP resin) WEP specimen was made with 3% MEK peroxide catalyst. The curing time was approximately seven minutes. The permeability of water through polyethylene is expected to be temperature dependent. However, it is also expected that when the specimen is cured and it cools down, the permeability of the polyethylene to water would be determined by the leachant temperature which in all cases was ambient. It is therefore unlikely that exposure of polyethylene to 97°C for seven minutes would permanently affect its water permeability.

The possibility of the WEP resin components altering the permeability characteristics of polyethylene was a much more likely explanation for the observation. To confirm this an emulsion of WEP resin and tritiated water of similar concentration as in specimens C1 and C2 was prepared in two identical containers to the ones used for C1 and C2. The emulsions, however, were not catalyzed. The containers were sealed the same way as containers for specimens C1, C2 and W1, W2 and designated as specimens C1A and C2A. The leaching behaviour, Figure 9 shows that the release rate (41.8×10^{-6} cm/day) is a factor of four higher than the catalyzed specimens and an order of magnitude higher than the unsolidified specimens W1, W2. This is clear evidence that the components of the WEP singly or in combination increase the water permeability and hence tritium release through polyethylene.

Effect of Container Thickness

The leaching behaviour of specimens PE1,2, PE3,4 and PE5,6 which are in containers of decreasing wall thickness is shown in Figure 10. As expected the tritium release rate decreases as the container wall thickness increases. The behaviour of the

replicates PE3, PE4 indicates that either there may be some leakage associated with specimen PE3 or the leachant surrounding PE3 may have become contaminated. Considering the variability of the leaching data associated with these specimens and the degree of interaction of the resin components with the polyethylene containers, the leaching behaviour with respect to the container thickness approximates a hyperbolic relationship as predicted by Equation (4).

Effect of Encapsulation

Encapsulating solidified and containerized specimens in a matrix of WEP resin gives rise to a cumulative fractional release rate of 1.4×10^{-6} cm/day (Figure 11). However, specimen E1 was observed to have shifted to one side during the curing which explains the large discrepancy between the data from the replicates E1 and E2. Data from E2 is therefore considered to be more representative of the encapsulation process. Table 5 compares the cumulative fractional release rates from solidified specimens under various packaging conditions. The effect of encapsulation is to lower the release rate by a factor of approximately 10^2. Comparing C1 and C2 with the unpackaged specimens 46, 47, the container also provides a reduction factor of approximately 10^2. Therefore, it might be expected that when both polyethylene and water extendible polyester resin form the barrier around the solidified specimen that the net reduction factor would be 10^4. The actual net reduction factor is however only 10^3. The most likely explanation is that in the specimens E1 and E2, the polyethylene container is functioning less effectively as a water barrier than in specimens C1 and C2 because of its exposure to the WEP resin components not only during the original solidification process as in C1 and C2, but also during the encapsulation process.

If the data from only E2 are considered, then the cumulative fractional release rate from encapsulation and containerization is 0.7×10^{-6} cm/day which is equivalent to the loss rate from PE1, PE2, the 1-cm thick containerized specimens. Since encapsulation is considerably more difficult than simple containerization there does not appear to be any advantage in pursuing the encapsulation route for tritium waste disposal certainly where the tritium is in the form of tritiated water.

Based on the above data, it is possible to calculate the experimentally derived value for the permeability constant $\underline{k}$ for HTO through polyethylene. This value can then be used to design the primary tritium barrier with respect to its thickness and dimension by calculating the theoretical permeation rate of HTO. If tritiated water covers a surface of area A and wall thickness ℓ, the rate of permeation is given by

$$R_{HTO} = \frac{k \cdot a_o \cdot A}{V \cdot \ell} \qquad (4)$$

TABLE 5

COMPARISON OF TRITIUM RELEASE RATES FROM COMPOSITES

Sample	Sample Description	Cumulative Fractional Release Rate (cm/day) x 10^6	Ref
46 47	Aqueous Waste Solidified in WEP Resin	1.1 x 10^3 ± 25.8	3
E19 E20	Solidified in WEP Resin and Encapsulated in 1 cm WEP Resin Layer	1.1 ± 0.3 (150 days) 14.0 ± 0.7 (750 days)	3
C1 C2	Solidification in WEP Resin Contained in 0.14 cm High Density Polyethylene	9.3 ± 1.6	This Work
E1 E2	Solidification in WEP Resin Contained in 0.14 cm HDPE and Encapsulated in 0.85 cm WEP Resin Layer	1.4 ± 0.7	This Work

where R_{HTO} is the rate of permeation of tritiated water (Ci/day) k is the permeability constant of tritiated water through polyethylene ($\frac{Ci.cm}{cm^2 \cdot Ci/cm^3 \cdot d}$),

a_o is the original tritium activity (Ci),

A is the surface area of polyethylene in contact with tritiated water (cm^2),

ℓ is the thickness of polyethylene container (cm),

V is the volume of water in contact with the polyethylene container (cm^3),

Equation (1) is derived in Appendix 2. Based on a published value of the permeability of water through high density polyethylene/4/ at 25°C a value of 4.1×10^{-7} $\frac{Ci.cm}{cm^2 \cdot Ci/cm^3 \cdot d}$ is calculated for k.

Table 6 shows that the calculated permeability constants for all the containerized samples agree very well with the published value. The values range from 1.9×10^{-7} to 9.3×10^{-7} $\frac{Ci \cdot cm}{cm^2 \cdot Ci/cm^3 \cdot d}$ for all specimens except the ones where the WEP resin is left uncured. For these specimens the calculated permeability constant is 2.75×10^{-6} $\frac{Ci.cm}{cm^2 \cdot Ci/cm^3 \cdot d}$. This value is similar to that obtained by other workers/5/, 2.2×10^{-6} $\frac{Ci \cdot cm}{cm^2 . Ci/cm^3 . d}$, who used low density polyethylene bottles. The effect of WEP resin components on polyethylene is apparently equivalent to lowering the density of polyethylene.

Considering this effect of solidification by WEP resin on the permeability of water through polyethylene, a value of 3×10^{-6} $\frac{Ci \cdot cm}{cm^2 \cdot Ci/cm^3 \cdot day}$ is assumed conservatively as the permeability constant for tritiated water through high density polyethylene. Therefore to meet a cumulative fractional release target of 1×10^{-5} per day from a 500-mL high density polyethylene container of area of approximately 350 cm^2 containing solidified tritiated waste in WEP resin would require a 0.4-cm thick container. If cement is used it is expected that the permeability constant would be closer to that calculated for the unsolidified specimens W1 and W2 because cement is not expected to increase

TABLE 6

CALCULATED PERMEABILITY CONSTANTS

Sample	Volume of Water in Sample (cm^3)	Cumulative Fractional Release Rate (day^{-1}) $\times 10^6$	Permeability Constant $k\left(\frac{Ci.cm}{cm^2.Ci/cm^3.d}\right)$ $\times 10^7$
W1 W2	450	1.1 ± 0.1	1.9 x 0.2
C1 C2	241.9	6.3 ± 1.1	5.6 ± 1.0
C1A C2A	245.0	28.4 ± 0.7	25.5 ± 0.6
C3 C4	45.0	6.8 ± 0.2	2.3 ± 0.1
C5 C6	11.2	12.7 ± 0.2	2.9 ± 0.1
PE1 PE2	244.5	0.5 ± 0.1	2.8 ± 0.6
PE3 PE4	237.7	3.1 ± 1.1	9.3 ± 3.3
PE5 PE6	238.7	5.5 ± 0.6	7.1 ± 0.8

the permeability of water through polyethylene. Consequently the container thickness could be reduced by as much as an order of magnitude and still meet the target release rate of 1×10^{-3}% per day. This however is being verified by experiment.

CONCLUSIONS AND RECOMMENDATIONS

(1) The tritiated water loss rate expressed as a fraction of the original activity increases approximately linearly with the ratio of the surface area to volume of the specimen and inversely with the thickness of the container.

(2) The permeability constant of tritiated water through polyethylene agrees well with published data ranging from 1.9 to 9.3×10^{-7} $\frac{Ci \cdot cm}{cm^2 \cdot Ci/cm^3 \cdot d}$. The higher range values are associated with those specimens where the polyethylene has been attacked to a significant degree by some components of the polymer resin.

(3) It is recommended that the nature of the interaction between the resin components and polyethylene be investigated further since it may be possible to treat the polyethylene with a suitable laminar barrier/6/ which would make it resistant to attack. This in turn would result in a further reduction in the rate of tritium loss from the waste packages and would allow thinner primary containers to be used.

(4) The exotherm generated during the curing of WEP resin is in excess of 95°C. Work in this laboratory and others have measured the exotherm associated with large scale cement specimens to be in excess of 100°C. Although the exotherms can be lowered by reducing the concentration of catalyst or the use of fillers in the case of cement solidification waste conditioning equipment should take into consideration the possibility of high ambient tritium concentrations in air due to evaporative losses from the solidified waste.

(5) Encapsulation by a 1-cm thick WEP resin matrix of solidified tritiated waste was shown in earlier work to reduce the tritium loss rate by a factor of 10^2. This same effective barrier to tritium losses can be achieved using a 1-mm thick polyethylene container for the solidified waste. Encapsulation therefore does not appear to be a cost effective option.

ACKNOWLEDGEMENT

The technical assistance of W. McPherson is gratefully acknowledged.

Approved by:

O.A. Rupcis
Manager
Chemical Research Dept

Prepared by:

J.P. Krasznai
Engineer
Organic Research Section

Reviewed by:

R.W. Glass
Supervising Chemist
Organic Research Section

JPK:am:ljh

REFERENCES

1. Garamszeghy, M. Darlington TRF: Summary of Radioactive Waste Generation, Handling and Storage, Report No 85091, March 1985.

2. Hawthorne, S.H. "Conditioning of Tritiated Wastes Part I - Tritiated Water Immobilization", Ontario Hydro Research Division Report No 82-531-K, 1982.

3. Hawthorne, S.H. "Conditioning of Tritiated Wastes Part II - Solidification and Encapsulation", Ontario Hydro Research Division Report No 84-6-K, 1984.

4. Crank, J. and Park, G.S. "Diffusion in Polymers", 1968, Academic Press.

5. Mershad, E.A., Thomasson, W.W. and Dauby, J.J. "Tritiated Liquid Waste Packaging", Mound Laboratory Report MLM-2440, Aug 1977.

6. Cordingley, D.C. Memo to Krasznai, J.P. File 837.83, July 1985.

APPENDIX 1

LEACHING DATA FOR TRITIATED AQUEOUS WASTE SPECIMENS

TABLE A.1.1

SAMPLE: W1 W2
SAMPLE DESCRIPTION: TRITIATED WATER UNSOLIDIFIED
SPECIMEN SURFACE AREA S: 337.4cm*2
SPECIMEN VOLUME V: 473.6cm*3
CONTAINER THICKNESS: 0.14cm
VOLUME OF WATER IN SPECIMEN: 450cm*3
INITIAL TRITIUM ACTIVITY: W1 130.56mCi
W2 130.56mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE (CFR*V/S)		
	W1 (uCi)	W2 (uCi)	W1 (cm)	W2 (cm)	AVG (cm)
1	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
2	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
3	0.23	0.22	2.48E-06	2.37E-06	2.43E-06
4	0.30	0.33	3.24E-06	3.56E-06	3.40E-06
7	0.78	0.83	8.41E-06	8.95E-06	8.68E-06
11	1.30	1.30	1.40E-05	1.40E-05	1.40E-05
17	2.11	2.21	2.28E-05	2.38E-05	2.33E-05
28	3.75	3.85	4.05E-05	4.15E-05	4.10E-05
50	6.47	6.57	6.98E-05	7.09E-05	7.03E-05
81	10.65	10.53	1.15E-04	1.14E-04	1.14E-04
100	13.46	13.35	1.45E-04	1.44E-04	1.45E-04
130	17.60	17.00	1.90E-04	1.83E-04	1.87E-04
170	23.69	22.77	2.56E-04	2.46E-04	2.51E-04
200	31.20	30.20	3.37E-04	3.26E-04	3.31E-04

TABLE A.1.2

SAMPLE: C1 C2
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN
SPECIMEN SURFACE AREA S:354.3cm*2
SPECIMEN VOLUME V:519.4cm*3
CONTAINER THICKNESS: 0.14cm
VOLUME OF WATER IN SPECIMEN: C1 246.6cm*3
C2 237.2cm*3
INITIAL TRITIUM ACTIVITY : C1 120.57mCi
C2 125.32mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	C1(uCi)	C2(uCi)	C1(cm)	C2(cm)	AVG(cm)
1	2.32	0.72	2.83E-05	8.45E-06	1.84E-05
2	4.38	1.42	5.34E-05	1.67E-05	3.50E-05
3	5.96	2.51	7.27E-05	2.95E-05	5.11E-05
4	7.16	3.25	8.73E-05	3.81E-05	6.27E-05
7	10.41	5.16	1.27E-04	6.06E-05	9.38E-05
11	14.69	8.43	1.79E-04	9.89E-05	1.39E-04
17	20.95	12.97	2.56E-04	1.52E-04	2.04E-04
28	31.76	20.99	3.87E-04	2.46E-04	3.17E-04
50	51.51	35.13	6.28E-04	4.12E-04	5.20E-04
81	79.04	55.57	9.64E-04	6.52E-04	8.08E-04
100	95.52	67.80	1.17E-03	7.96E-04	9.80E-04
130	119.00	85.50	1.45E-03	1.00E-03	1.23E-03
170	159.57	118.68	1.95E-03	1.39E-03	1.67E-03
200	200.80	148.90	2.45E-03	1.75E-03	2.10E-03

TABLE A.1.3

SAMPLE: C1A C2A
SAMPLE DESCRIPTION: TRITIATED WATER IN AN UNCATALYZED
WEP RESIN EMULSION
SPECIMEN SURFACE AREA S:354.3cm*2
SPECIMEN VOLUME V:519.4cm*3
CONTAINER THICKNESS: 0.14cm
VOLUME OF WATER IN SPECIMEN: C1A 240cm*3
C2A 250cm*3
INITIAL TRITIUM ACTIVITY: C1A 151.68mCi
C2A 158.00mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	C1A(uCi)	C2A(uCi)	C1A(cm)	C2A(cm)	AVG(cm)
1	1.24	1.27	1.20E-05	1.18E-05	1.19E-05
2	2.97	3.00	2.88E-05	2.79E-05	2.84E-05
4	6.62	6.88	6.42E-05	6.40E-05	6.41E-05
25	66.09	66.39	6.41E-04	6.18E-04	6.29E-04
80	325.38	324.49	3.15E-03	3.02E-03	3.09E-03
100	408.30	410.60	3.96E-03	3.82E-03	3.89E-03
144	605.27	601.65	5.87E-03	5.60E-03	5.73E-03

TABLE A.1.4

SAMPLE: C3 C4
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN
SPECIMEN SURFACE AREA S:117.9cm*2
SPECIMEN VOLUME V:99.9cm*3
CONTAINER THICKNESS:0.09cm
VOLUME OF WATER IN SPECIMEN: C3 44.6cm*3
C4 45.4cm*3
INITIAL TRITIUM ACTIVITY: C3 101.89mCi
C4 103.72mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	C3(uCi)	C4(uCi)	C3(cm)	C4(cm)	AVG(cm)
1	0.84	0.92	6.99E-06	7.52E-06	7.25E-06
2	1.93	2.07	1.61E-05	1.69E-05	1.65E-05
3	3.05	3.05	2.54E-05	2.49E-05	2.51E-05
4	3.93	4.28	3.27E-05	3.50E-05	3.38E-05
7	6.31	7.07	5.25E-05	5.78E-05	5.51E-05
11	10.25	11.45	8.53E-05	9.36E-05	8.94E-05
17	15.20	15.90	1.26E-04	1.30E-04	1.28E-04
28	25.21	25.31	2.10E-04	2.07E-04	2.08E-04
50	41.37	40.35	3.44E-04	3.36E-04	3.40E-04
81	63.66	61.56	5.30E-04	5.12E-04	5.21E-04
100	77.21	73.59	6.42E-04	6.12E-04	6.27E-04
130	94.90	89.10	7.89E-04	7.41E-04	7.65E-04
170	128.03	121.08	1.06E-03	1.01E-03	1.04E-03
200	164.30	152.60	1.37E-03	1.27E-03	1.32E-03

TABLE A.1.5

SAMPLE: C5 C6
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN
SPECIMEN SURFACE AREA S:48.2cm*2
SPECIMEN VOLUME V:25.1cm*3
CONTAINER THICKNESS: 0.07cm
VOLUME OF WATER IN SPECIMEN: C5 11.1cm*3
C6 11.2cm*3
INITIAL TRITIUM ACTIVITY: C5 129.42mCi
C6 130.58mCI

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	C5(uCi)	C6(uCi)	C5(cm)	C6(cm)	AVG(cm)
1	2.17	3.49	8.73E-06	1.39E-05	1.13E-05
2	5.02	7.14	2.02E-05	2.85E-05	2.43E-05
3	8.08	10.34	3.25E-05	4.12E-05	3.69E-05
4	10.14	12.70	4.08E-05	5.07E-05	4.57E-05
7	15.47	18.66	6.23E-05	7.44E-05	6.83E-05
11	25.38	28.59	1.02E-04	1.14E-04	1.08E-04
17	37.27	41.50	1.50E-04	1.66E-04	1.58E-04
28	59.51	64.34	2.39E-04	2.57E-04	2.48E-04
50	96.88	102.19	3.90E-04	4.11E-04	4.01E-04
81	145.50	153.07	5.86E-04	6.16E-04	6.01E-04
100	174.79	184.42	7.03E-04	7.42E-04	7.23E-04
130	212.60	223.30	8.56E-04	8.99E-04	8.77E-04
170	285.81	298.56	1.15E-03	1.20E-03	1.18E-03
200	362.90	378.30	1.46E-03	1.52E-03	1.49E-03

TABLE A.1.6

SAMPLE: PE1 PE2
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN
SPECIMEN SURFACE AREA S:443.0cm*2
SPECIMEN VOLUME V:722.6cm*3
CONTAINER THICKNESS: 1.0cm
VOLUME OF WATER IN SPECIMEN: PE1 239.8cm*3
PE2 249.2cm*3
INITIAL TRITIUM ACTIVITY: PE1 117.50mCi
PE2 122.11mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	PE1(uCi)	PE2(uCi)	PE1(cm)	PE2(cm)	AVG(cm)
1	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
2	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
3	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
4	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
7	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
11	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
17	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
28	0.78	0.57	1.09E-05	7.65E-06	9.27E-06
50	2.10	1.58	2.93E-05	2.20E-05	2.57E-05
81	4.04	3.18	5.64E-05	4.44E-05	5.04E-05
100	5.50	4.48	7.67E-05	6.25E-05	6.96E-05
130	7.20	5.90	1.00E-04	8.23E-05	9.14E-05
170	9.82	9.18	1.37E-04	1.28E-04	1.33E-04
200	12.80	11.90	1.79E-04	1.66E-04	1.72E-04

TABLE A.1.7

SAMPLE: PE3 PE4
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN
SPECIMEN SURFACE AREA S:395.1cm*2
SPECIMEN VOLUME V:601.2cm*3
CONTAINER THICKNESS 0.50cm
VOLUME OF WATER IN SPECIMEN: PE3 240.4cm*3
PE4 234.9cm*3
INITIAL TRITIUM ACTIVITY: PE3 117.80mCi
PE4 115.08mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	PE3(uCi)	PE4(uCi)	PE3(cm)	PE4(cm)	AVG(cm)
1	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
2	0.37	0.13	4.76E-06	1.67E-06	3.22E-06
3	1.00	0.40	1.29E-05	5.15E-06	9.00E-06
4	1.60	0.58	2.06E-05	7.46E-06	1.40E-05
7	3.44	1.36	4.42E-05	1.75E-05	3.09E-05
11	4.65	2.25	5.98E-05	2.89E-05	4.44E-05
17	6.42	3.61	8.26E-05	4.64E-05	6.45E-05
28	10.11	6.12	1.30E-04	7.87E-05	1.04E-04
50	19.55	11.13	2.51E-04	1.43E-04	1.97E-04
81	34.38	19.20	4.42E-04	2.47E-04	3.45E-04
100	44.39	23.42	5.71E-04	3.01E-04	4.36E-04
130	57.40	29.50	7.38E-04	3.79E-04	5.59E-04
170	80.10	39.70	1.03E-03	5.11E-04	7.70E-04
200	103.50	49.30	1.33E-03	6.34E-04	9.83E-04

TABLE A.1.8

SAMPLE: PE5 PE6
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN
SPECIMEN SURFACE AREA S:368.6cm*2
SPECIMEN VOLUME V:539.4cm*3
CONTAINER THICKNESS:0.20cm
VOLUME OF WATER IN SPECIMEN: PE5 236.8cm*3
PE6 240.6cm*3
INITIAL TRITIUM ACTIVITY: PE5 116.03mCi
PE6 117.87mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	PE5(uCi)	PE6(uCi)	PE5(cm)	PE6(cm)	AVG(cm)
1	0.44	0.24	5.58E-06	2.99E-06	4.29E-06
2	1.50	0.91	1.90E-05	1.14E-05	1.52E-05
3	2.38	1.55	3.02E-05	1.93E-05	2.48E-05
4	2.83	2.18	3.59E-05	2.72E-05	3.15E-05
7	4.78	4.71	6.06E-05	5.88E-05	5.97E-05
11	6.64	7.96	8.42E-05	9.93E-05	9.17E-05
17	9.87	14.45	1.25E-04	1.80E-04	1.53E-04
28	18.84	24.23	2.39E-04	3.02E-04	2.71E-04
50	38.64	46.97	4.90E-04	5.95E-04	5.43E-04
81	58.59	71.17	7.43E-04	9.02E-04	8.22E-04
100	71.71	86.27	9.09E-04	1.09E-03	1.00E-03
130	85.40	106.40	1.08E-03	1.35E-03	1.22E-03
170	106.29	133.90	1.35E-03	1.70E-03	1.52E-03
200	128.70	165.20	1.63E-03	2.09E-03	1.86E-03

TABLE A.1.9

SAMPLE: E1 E2
SAMPLE DESCRIPTION: TRITIATED WATER SOLIDIFIED IN WEP RESIN AND ENCAPSULATED IN A WEP MATRIX
SPECIMEN SURFACE AREA S:370.9cm*2
SPECIMEN VOLUME V:822.5cm*3
CONTAINER THICKNESS:0.14cm
ENCAPSULATING LAYER THICKNESS:0.85cm
VOLUME OF TRITIATED WATER IN SPECIMENS: E1 234.5cm*3
E2 234.0cm*3
INITIAL TRITIUM ACTIVITY: E1 119.19mCi
E2 118.94mCi

TIME (DAYS)	CUMULATIVE RELEASE		CUMULATIVE FRACTIONAL RELEASE(CFR*V/S)		
	E1(uCi)	E2(uCi)	E1(cm)	E2(cm)	AVG(cm)
1	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
2	0.00	0.00	0.00E+00	0.00E+00	0.00E+00
3	0.07	0.00	1.31E-06	0.00E+00	6.53E-07
4	0.17	0.00	3.17E-06	0.00E+00	1.58E-06
7	0.60	0.00	1.12E-05	0.00E+00	5.59E-06
11	1.27	0.00	2.37E-05	0.00E+00	1.18E-05
17	2.00	0.00	3.73E-05	0.00E+00	1.86E-05
28	3.42	0.00	6.38E-05	0.00E+00	3.19E-05
50	6.54	0.00	1.22E-04	0.00E+00	6.10E-05
81	8.11	0.14	1.51E-04	2.61E-06	7.69E-05
100	10.48	0.51	1.95E-04	9.51E-06	1.02E-04
130	13.70	1.10	2.55E-04	2.05E-05	1.38E-04
170	16.93	2.73	3.16E-04	5.09E-05	1.83E-04
200	21.10	4.60	3.93E-04	8.58E-05	2.40E-04

APPENDIX 2

PERMEABILITY OF TRITIATED WATER THROUGH POLYETHYLENE

If liquid water is in contact with a container surface, the total rate of permeation is given by:

$$R_{H_2O} = K\, P^{(s)}_{H_2O} \cdot \frac{A}{\ell} \qquad (1)$$

where R_{H_2O} is the rate of permeation of water vapour

K is the permeability coefficient

$P^{(s)}_{H_2O}$ · is the saturation vapour pressure of water at a given temperature

A is the surface area of container in contact with water vapour

ℓ is the thickness of container

If water contains a certain mole fraction of tritiated water (f) then $R_{HTO} = f\, R_{H_2O}$ (2)

$$\therefore\ R_{HTO} = f\, KP^{(s)}_{H_2O} \cdot \frac{A}{\ell} \qquad (3)$$

where $f = \dfrac{\text{number of moles of HTO}}{\text{number of moles of water}} = \dfrac{a_o}{a_m} \cdot \dfrac{V_m}{V}$

where a_o is the tritium activity in Curies
a_m is the molar tritium activity (in Curies per mole HTO)
V is the water volume V in litres
V_m is the molar water volume in litres per mole water

$$R_{HTO} = K \cdot P^{(s)}_{H_2O} \cdot \frac{V_m}{a_m} \left(\frac{a_o . A}{\ell \cdot V}\right)$$

where $k = KP^{(s)}_{H_2O} \cdot \dfrac{V_m}{a_m}$

To obtain value of k

$V_m = 18 \times 10^{-3}$ L mol^{-1}

$$a_m = \frac{N_A \lambda}{3.7 \times 10^{10}} \text{ Ci mol}^{-1}$$

where N_A = Avogadro's Number
$= 6.02 \times 10^{+23}$ Molecules mol^{-1}
λ = decay const for ^3H
$= 1.78 \times 10^{-9}$ s^{-1}

$a_m = 2.90 \times 10^4$ Ci mol^{-1}

$$K = 2.5 \times 10^{-9} \quad \frac{\text{cm}^3(\text{STP})\text{cm}^{-2}\ \text{s}^{-1}}{\text{cm-Hg}.\text{cm}^{-1}} \text{ at } 25^\circ \text{ C for HDPE (Reference 4)}$$

$P^{(s)}_{H_2O}$ @ 25° C = 2.37 cm-Hg

To obtain correct units, it is necessary to express K in terms of $\frac{\text{Ci}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}}{\text{cm-Hg}\cdot\text{cm}^{-1}}$.

Assuming tritiated water vapour behaves as an ideal gas as it permeates through polyethylene:

1 mole HTO at STP occupies 22.4×10^3 cm^3

$\frac{6.02 \times 10^{23} \times 1.78 \times 10^{-9}}{3.7 \times 10^{10}}$ Curies occupies 22.4×10^3 cm^3

$\therefore$ 1 cm^3 contains 1.29 Curies HTO

$$K = (2.5 \times 10^{-9})(1.29) \quad \frac{\text{Ci}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}}{\text{cm-Hg}\cdot\text{cm}^{-1}}$$

$$= 3.23 \times 10^{-9} \quad \frac{\text{Ci}\cdot\text{cm}^{-2}\cdot\text{s}^{-1}}{\text{cm-Hg}\cdot\text{cm}^{-1}}$$

$$\therefore k = \frac{3.23\times10^{-9} \times 2.37 \times 18\times10^{-3}}{2.90 \times 10^{4}} \quad \frac{Ci\cdot cm}{cm^2\cdot Ci/L\cdot s}$$

$$= 4.75\times10^{-15} \quad \frac{Ci\cdot cm}{cm^2\ Ci/L\cdot s}$$

$$= 4.10\times10^{-7} \quad \frac{Ci\cdot cm}{cm^2\cdot Ci/cm^3\cdot d}$$

LIST OF FIGURES

FIGURE 1 MULTIBARRIER CONCEPT FOR PACKAGING TRITIATED WASTE

FIGURE 2 POLYETHYLENE CONTAINERS AND SEALING ARRANGEMENT

FIGURE 3 TECHNIQUE FOR ENCAPSULATING SPECIMENS

FIGURE 4 CUMULATIVE FRACTIONAL RELEASE vs TIME FOR SPECIMENS C1 AND C2

FIGURE 5 CUMULATIVE FRACTIONAL RELEASE vs TIME FOR SPECIMENS C3 AND C4

FIGURE 6 CUMULATIVE FRACTIONAL RELEASE vs TIME FOR SPECIMENS C5 AND C6

FIGURE 7 CUMULATIVE FRACTIONAL RELEASE vs TIME FOR SPECIMENS C1,2, C3,4, C5,6

FIGURE 8 CUMULATIVE FRACTIONAL RELEASE (cm) [normalized to constant surface area/volume ratio] vs TIME FOR SPECIMENS C1, C2, C3, C4, C5, C6

FIGURE 9 CUMULATIVE FRACTIONAL RELEASE (cm) vs TIME FOR SPECIMENS C1, 2, W1, 2 and C1A, 2A

FIGURE 10 CUMULATIVE FRACTIONAL RELEASE (cm) vs TIME FOR SPECIMENS PE1,2, PE3,4 AND PE5,6

FIGURE 11 CUMULATIVE FRACTIONAL RELEASE (cm) vs TIME FOR C1,2 PE1,2, W1,2 and E1,2

FIGURE 12 CUMULATIVE FRACTIONAL RELEASE RATE (cm/day) vs SURFACE AREA/VOLUME RATIO

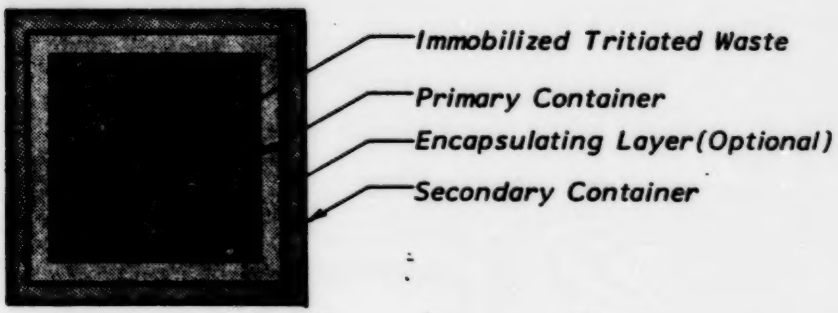


FIGURE 1

MULTIBARRIER CONCEPT FOR PACKAGING TRITIATED WASTE

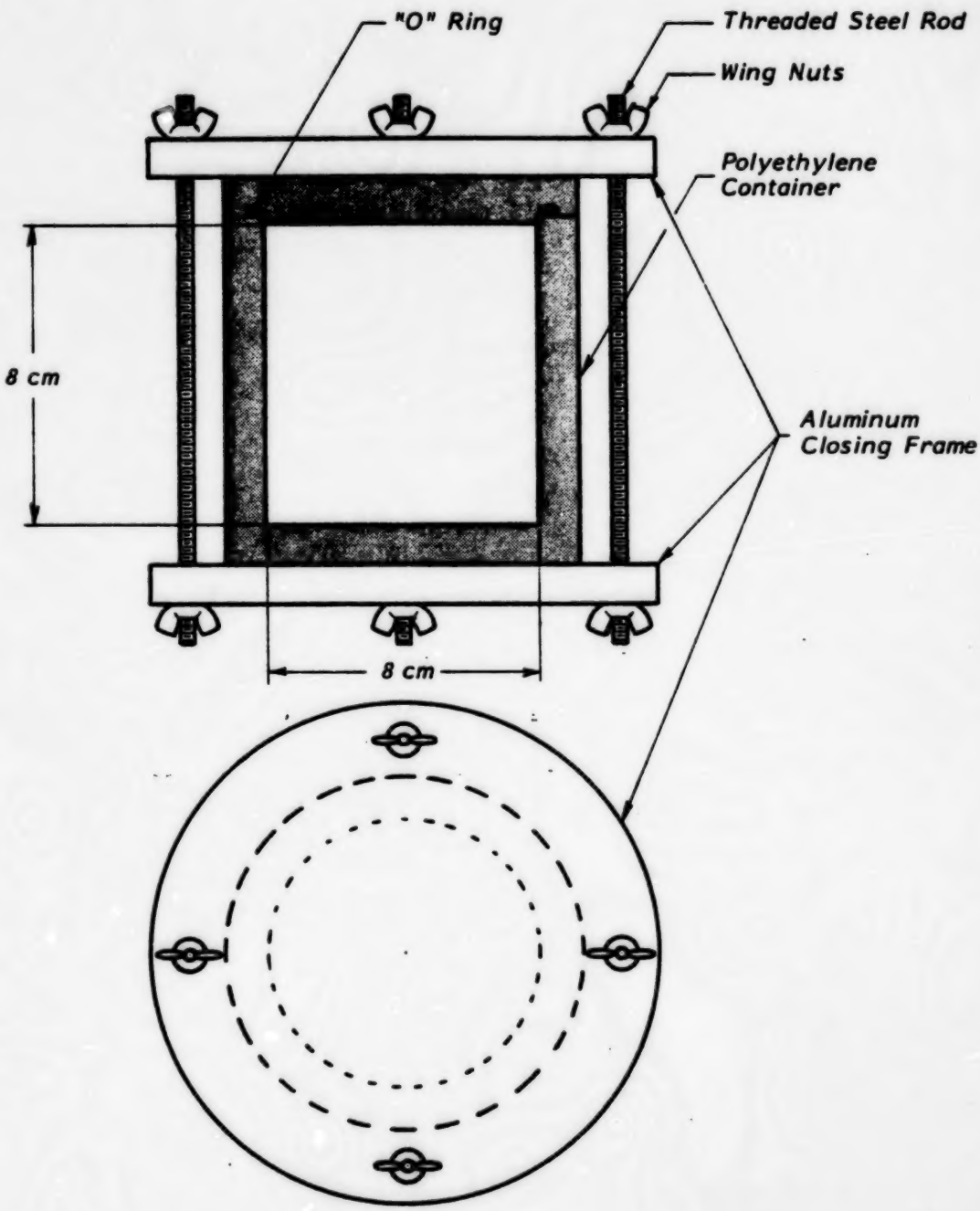


FIGURE 2

1 CM, 0.5 CM, 0.2 CM POLYETHYLENE CONTAINERS AND SEALING ARRANGEMENT

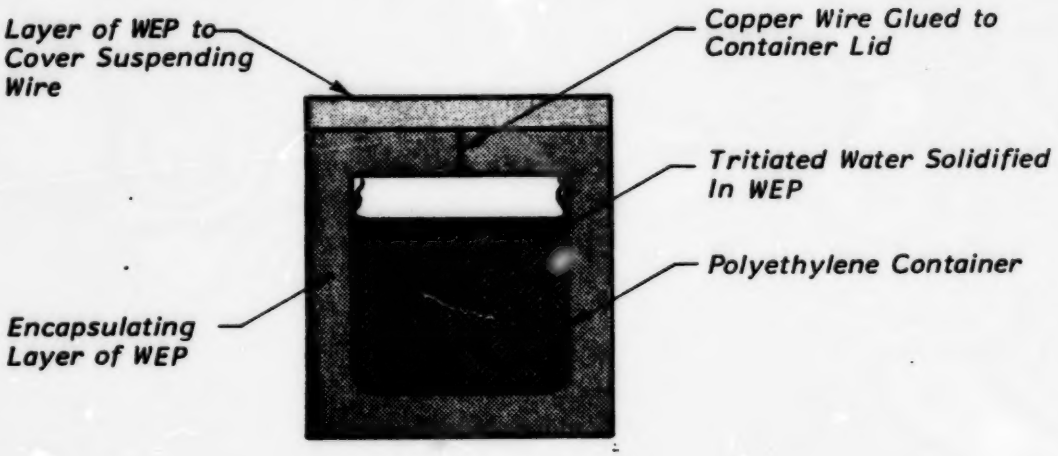

Layer of WEP to Cover Suspending Wire
Copper Wire Glued to Container Lid
Tritiated Water Solidified In WEP
Polyethylene Container
Encapsulating Layer of WEP

FIGURE 3

TECHNIQUE FOR ENCAPSULATING SPECIMENS

FIGURE 4

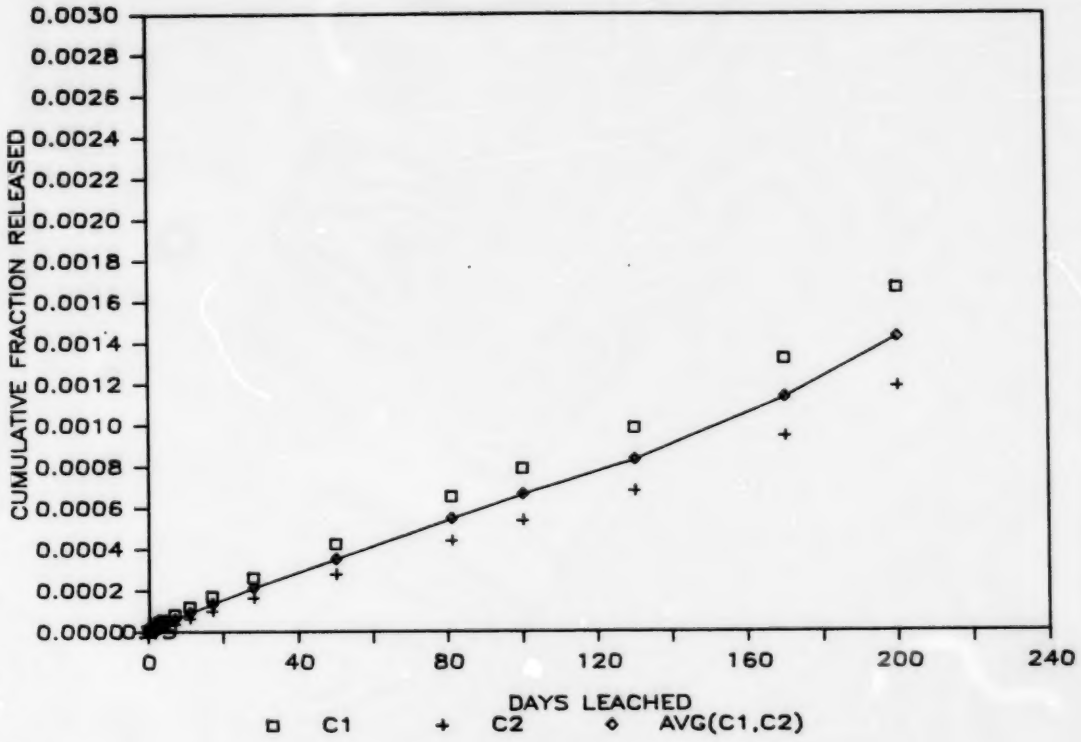


FIGURE 5

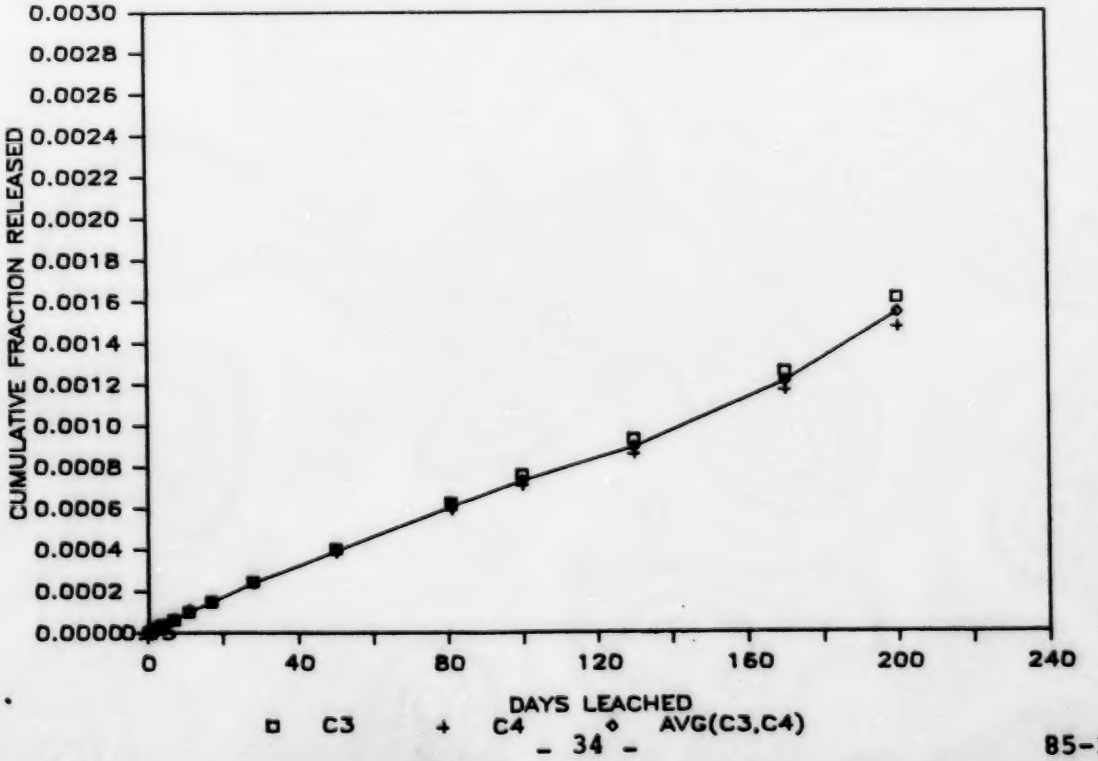


FIGURE 6

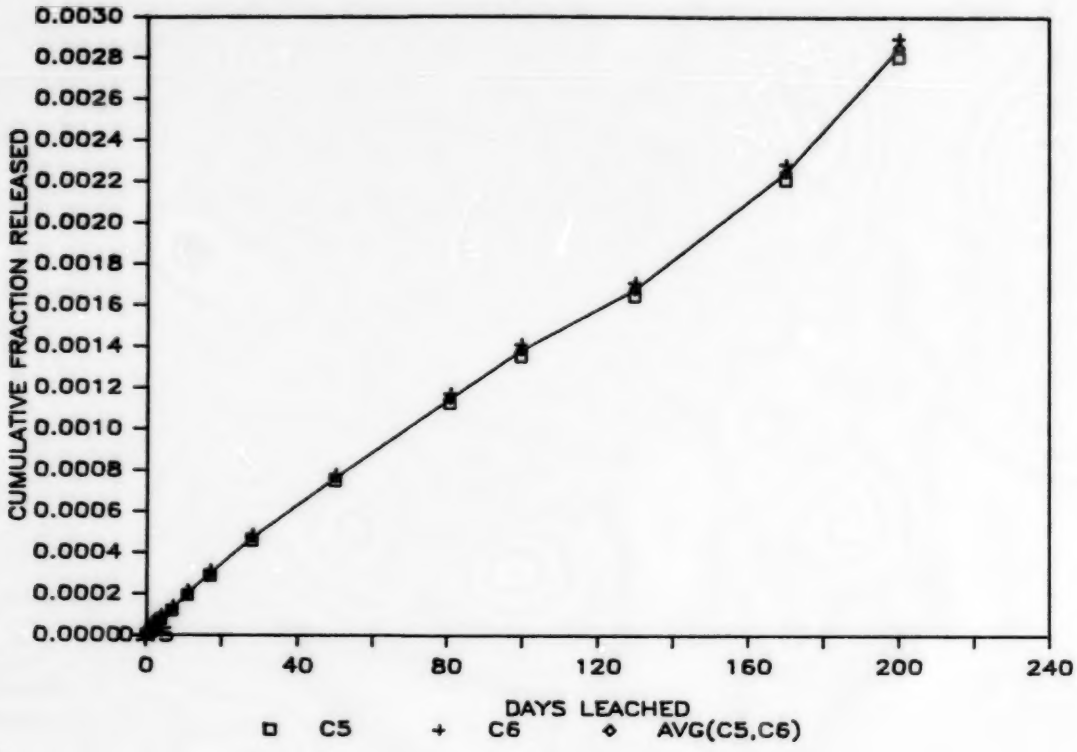


FIGURE 7

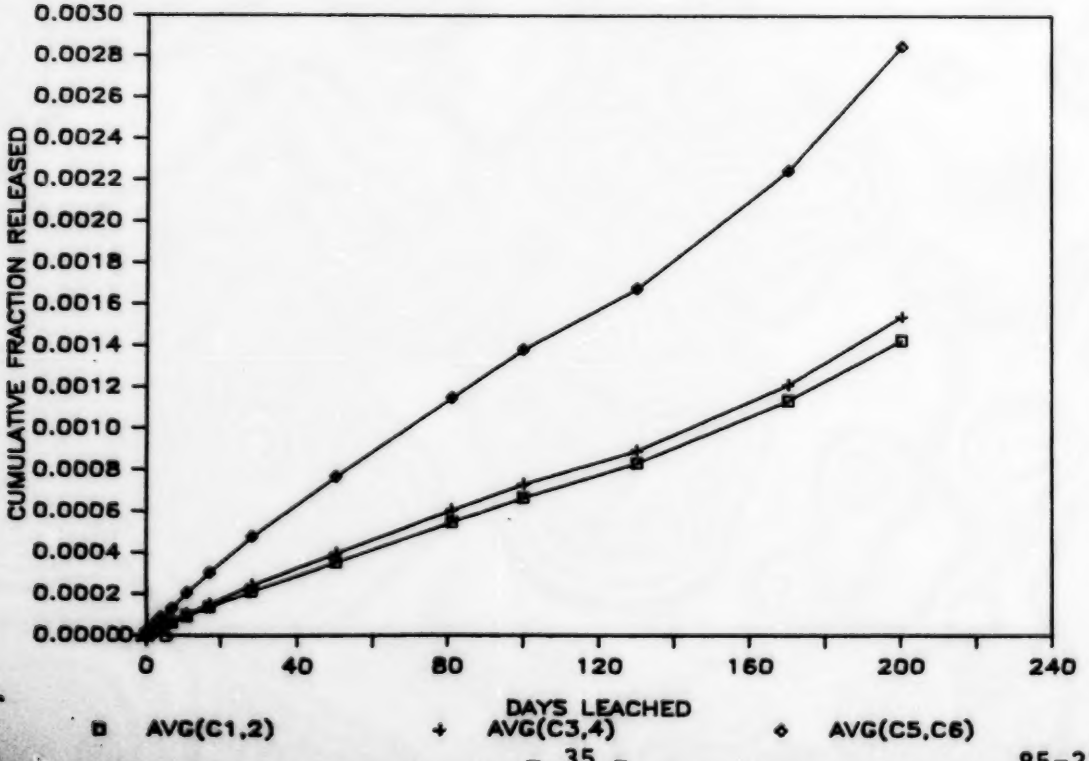


FIGURE 8

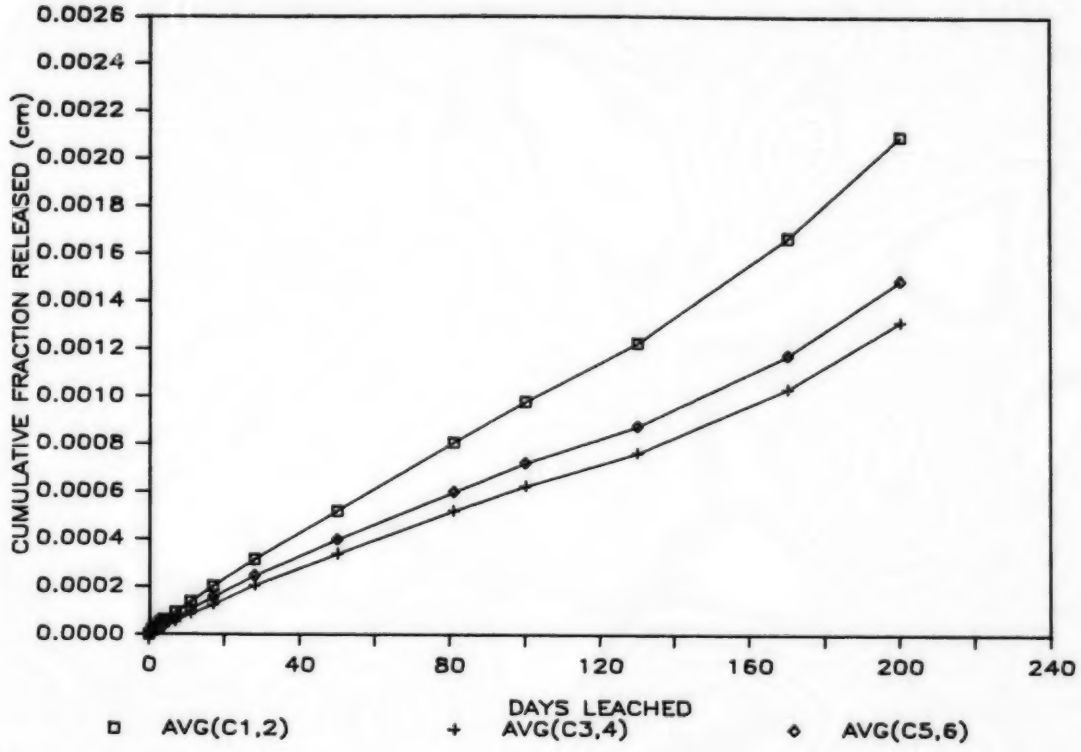


FIGURE 9

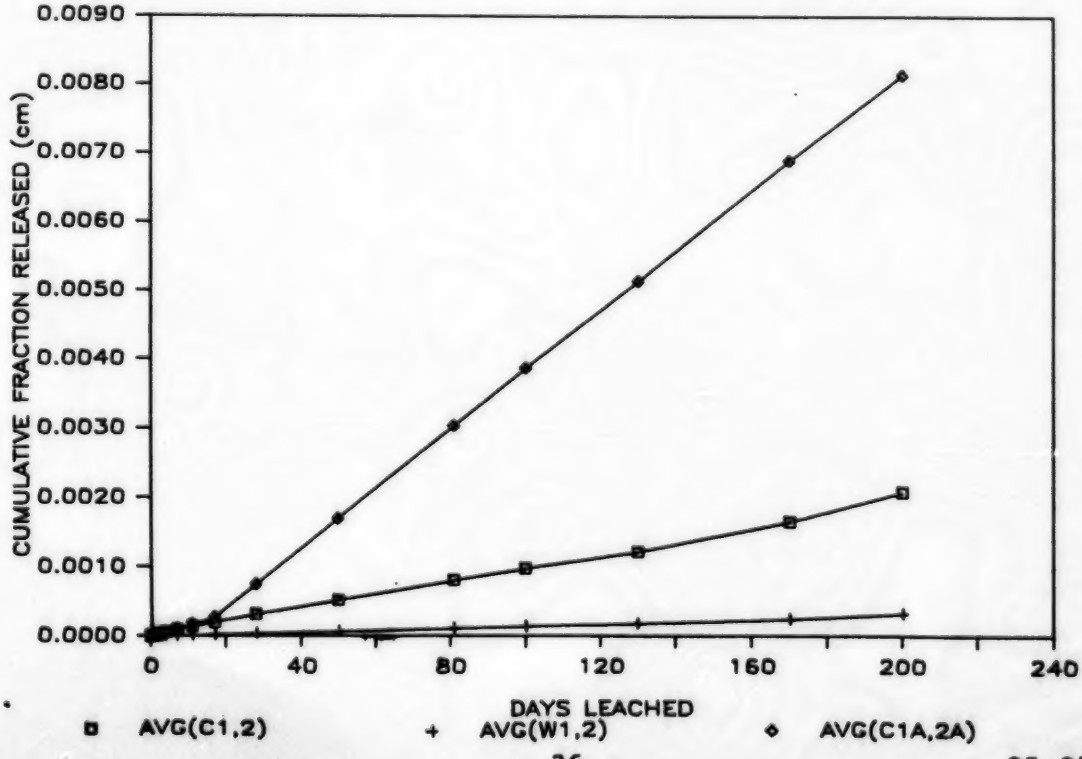


FIGURE 10

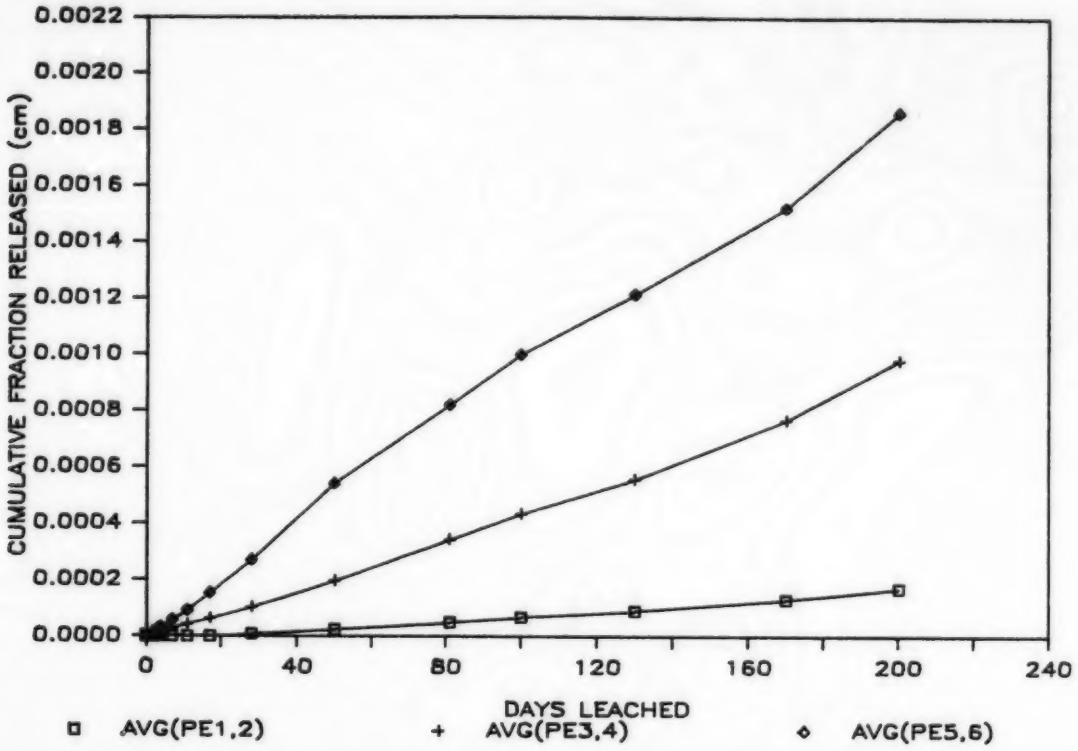


FIGURE 11

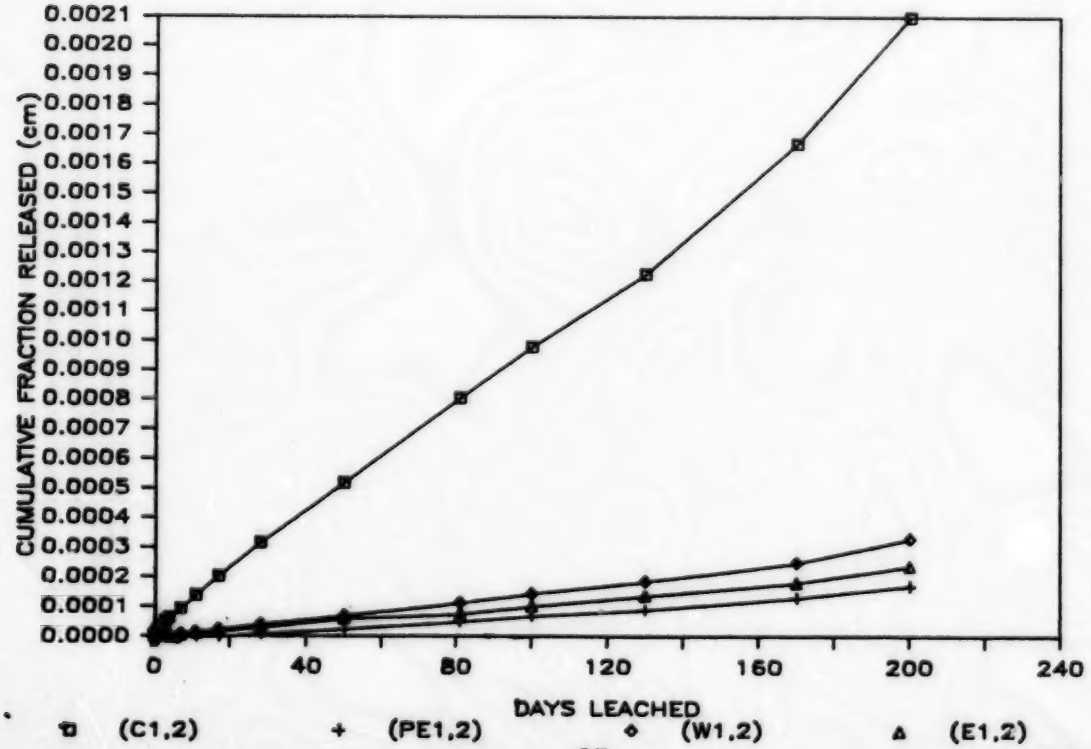
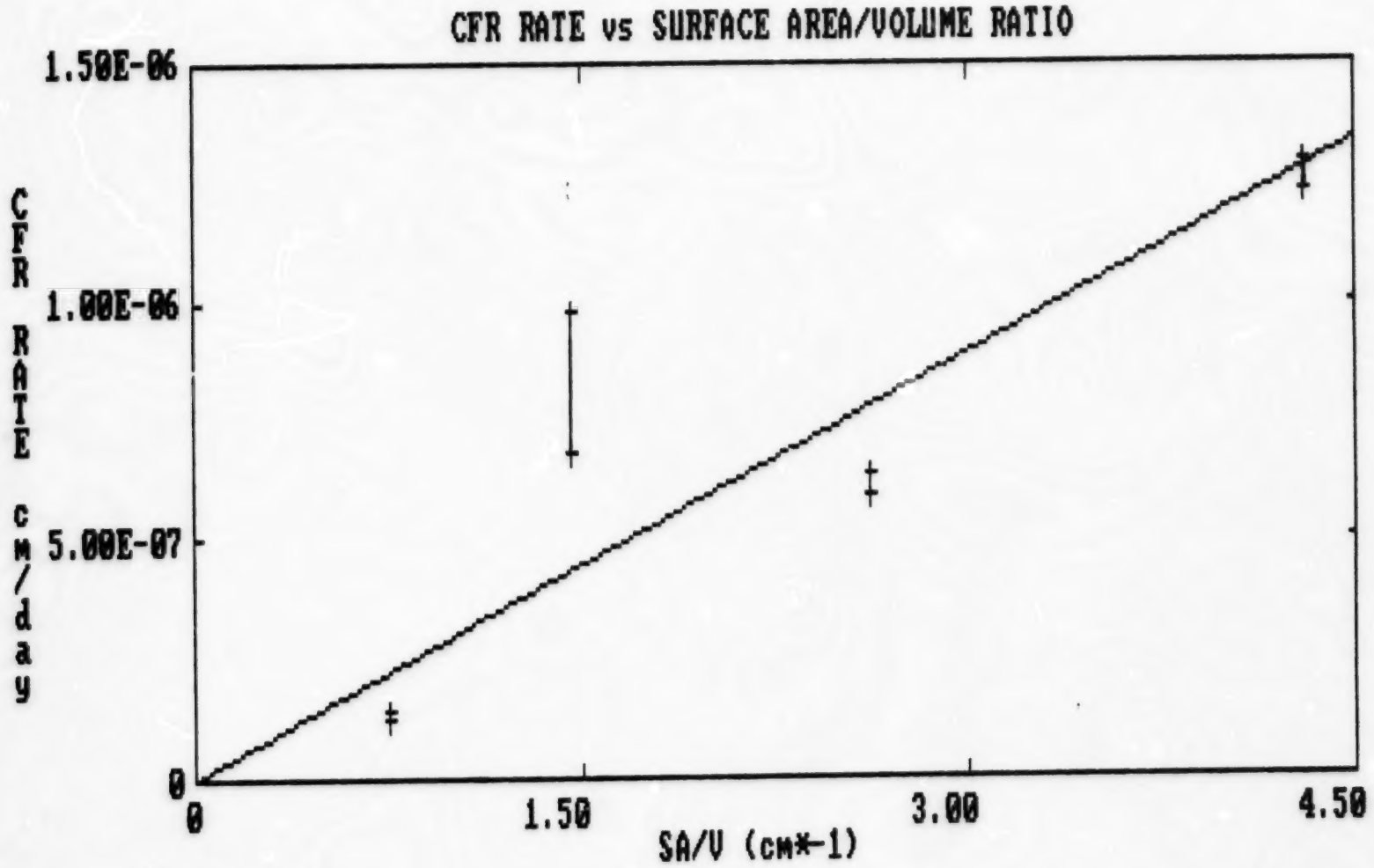


FIGURE 12


CFR RATE vs SURFACE AREA/VOLUME RATIO
1.50E-06
1.00E-06
5.00E-07
0
CFR RATE cm/day
0
1.50
3.00
4.50
SA/V (cm*-1)